Essentials and Uniqueness of 3-D Global Particle Simulations

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How to understand and use TRISTAN code

Computer Simulation Using Particles
by R.W. Hockney, J.W. Eastwood

Plasma Physics Via Computer Simulation / Book and Disk
by C. K. Birdsall, A. B. Langdon

Computer Space Plasma Physics: Simulation Technique and Software edited by H. Matsumoto and Y. Omura

Chapters 2. KEMPO01 and 3. TRISTAN

Comments provided in the both codes

This notes presented at ISSS-6

Outline

- **A brief history of global simulations**
- **Introduction**
  - **A brief tour of magnetosphere**
  - **Basic equations**
  - **Plasma parameters**
- **Global structure of code**
  - **Initialization, Field update, Particle update, Interpolation, Charge fluxes, Smoothing, Boundary conditions**
- **Post processing**
- **Global Solar Wind-Magnetosphere Interactions**
- **Future work**

Other methods

- MHD simulations

  without kinetic effects

- Hybrid simulations

  electrons fluids

- Tailored simulations

  work well with local simulations

- Simulations with modules

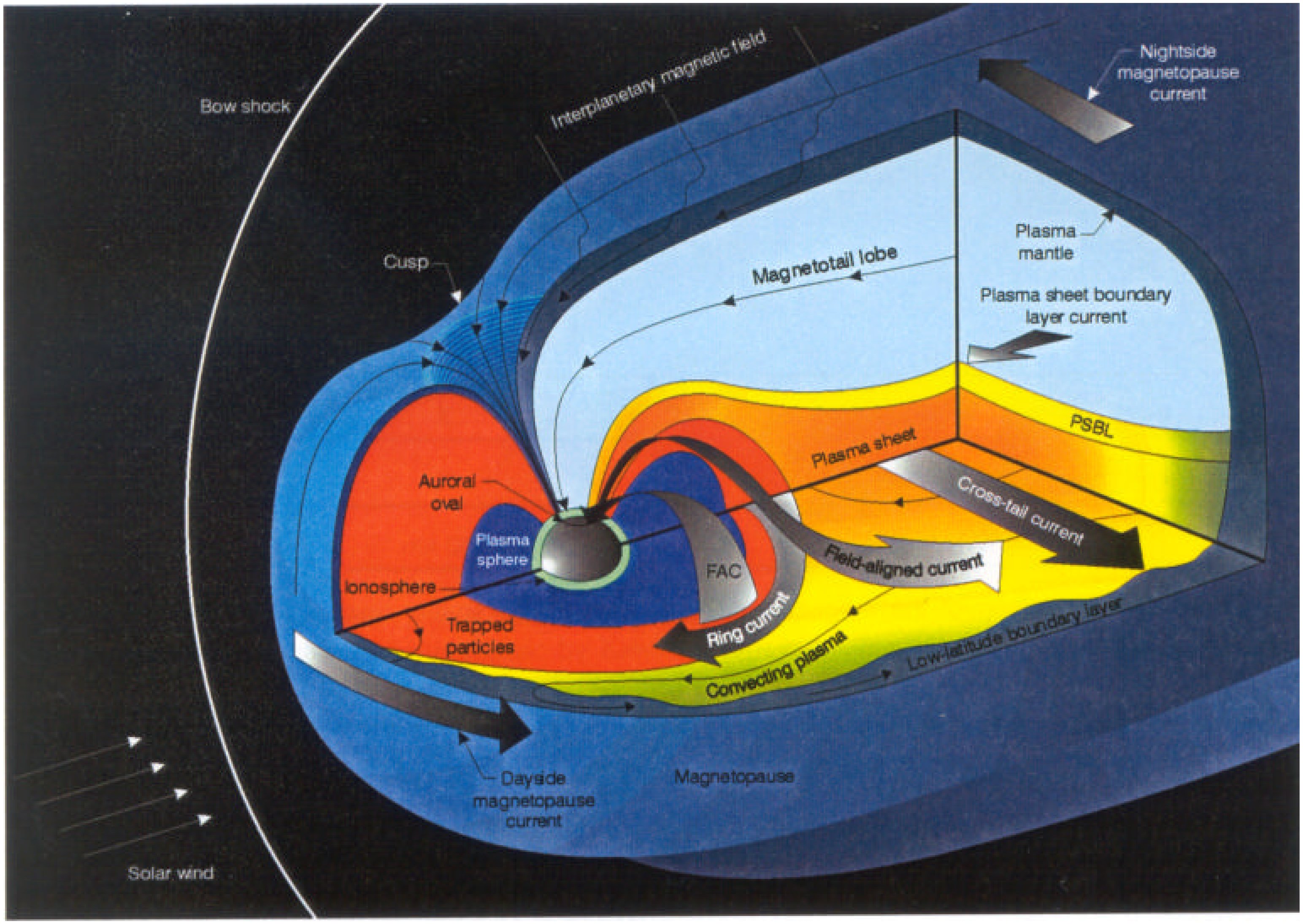
  difficult to combine with other methods

- Particle simulations

  difficult to establish spatial and temporal resolutions

A brief history of global simulations

- **1978: First 2-D MHD simulations by Leboeuf et al.**
- **Early 80’s: First 3-D MHD simulations (Brecht, Lyon, Wu, Ogino)**
- **Late 80’s: Model refinements (FACs, ionosphere, higher resolution, fewer symmetries)**
- **Early 90’s: Long geomagnetic tail, refined ionosphere models.**
- **1992: First global particle simulation (Buneman et al.)**
- **Mid 90’s: ISTP is well under way, first comparisons with *in situ* space observations and ground based observations. Beginning of *quantitative modeling*.**
- **1997: First particle simulations with IMF (Nishikawa)**
- **Late 90’s: Global modeling has become an integrated part of many experimental studies. Models provide an extension to spatially limited observations and help us to understand the physics**
- **2000: A substorm model by global particle simulation (Nishikawa)**



What triggers a substorm?

How are high energy particles injected during magnetic storms?

How is a ring current generated and dissipated?

Present global particle simulations can do

Reproduce the gross features of Magnetosphere including

a reasonable representation of

- **the bow shock**
- **the magnetopause**
- **the cusps**
- **the magnetotail**
- **the effects of the IMFs**
- **fields and currents**

Reproduce the fundamental features of the dynamic Magnetosphere:

- **substorms**
- **transient events due to variations of solar wind conditions**
- **convections**

Why do we need to do particle simulations?

***In MHD simulations kinetic effects are not included**

- **Þ dynamics of boundaries are not properly simulated**
- **Þ particle injections are not included,**
  in particular accelerated high energy particles
- **Þ ring current is not included in the present time**

***Computer power (memory and speed) will be available in ten years or so in order to perform global particle simulations for quantitative comparisons with observations including velocity distributions**

***Prepare for future missions such as MMS and MC DRACO in order to provide useful information for planning and data analysis**

***Predictions of high energy particle injections for Space Weather**

Basic equations

Maxwell equations

$\partial \boldsymbol{B}/\partial t = -\nabla\times\boldsymbol{E}$ and $\partial \boldsymbol{D}/\partial t = \nabla\times\boldsymbol{H} - \boldsymbol{J}$

As well as Newton-Lorentz (relativistic)

$dm\boldsymbol{v}/d\boldsymbol{t} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$

$\varepsilon_0 = 1$ and hence $\mu_0 = 1/c^2$

$\boldsymbol{D} = \boldsymbol{E}$ and $\boldsymbol{B} \rightarrow c\boldsymbol{B}$

$\boldsymbol{E} \Leftrightarrow \boldsymbol{B}$ (symmetric)

Plasma parameters

$\omega_e = (nq_e^2/m_e)^{1/2}$: electron plasma frequency

$\omega_i = (nq_i^2/m_i)^{1/2}$: ion plasma frequency

$\Omega_e = q_eB/m_e$: electron gyrofrequency

$\Omega_i = q_iB/m_i$: ion gyrofrequency

$\lambda_e = v_e/\omega_e$: electron Debye length

$\lambda_i = v_i/\omega_i$: ion Debye length

$\lambda_{ce} = c/\omega_e$: electron inertia length

$\lambda_{ci} = c/\omega_i$: ion inertia length

$\Delta x \geq 3\lambda_e$:(to avoid numerical instability)

$\Delta t \leq \Delta x/c$: Courant condition ($c = 0.5$)

if $c = 10v_e$, $T_i = T_e$, and $m_i = 16\ m_e$

$\lambda_e << \lambda_i << \lambda_{ce} << \lambda_{ci}$

1 4 10 40

Numerical considerations

- **Scale Size**
  - ➤ **the scale of the system ranges from 10s of Kms in the ionosphere to 100s of Earth radii in the far tail.**
  - ➤ **physical values vary up to 7 orders of magnitude, e.g., ρ » $(10^{-1} – 10^{4})$, B » $(10^{-2} – 10^{4})$, β » $(10^{-5} – 10^{2})$, n » $(10^{-2} – 10)$**
- **Time step**
  - ➤ **the smallest time step is considered by the fastest wave speed in the system, which is of order of the fast mode speed – this can be very high near the Earth.**
- **Verification**
  - ➤ **one of the best tests of a numerical method is to compare its results with observations – however, since the observations are usually single or dual, the comparisons are not easy or comprehensive.**

Main streams of code

Simulation arrays, parameters, commons

Open files, read data

Initialization (solar wind particles, dipole etc)

$B(n+1) = B(n) + 0.5*E(n)\Delta t$

Push particles

$B(n+1) = B(n) + 0.5*E(n)\Delta t$

Surface, postedge, preledge

$E(n+1) = E(n) + B(n)\Delta t$

Current charge fluxes: x-, y-, zsplip, depsit

Checking particles at the boundaries

Inject solar wind particles at $x = x_s$

At the last step write data for restart

Field Update

Space-time symmetry $\Leftrightarrow$ space- and time centered

Postprocessing

- **Snapshots (NCARG, Techplot, AVS)**

  electron (ion) density at any cross-sections

  with arrows (magnetic fields, fluxes)

  electron (ion) flux (velocity) with arrows

  (flux (velocity) in the cross-section)

  3-D displays of isosurface

  streamlines of magnetic fields (velocity)

- **Time-dependent**

  movies (electron density, magnetic field lines, etc)

  local electromagnetic fields (E, B)

  sheet currents in the tail

- **Requires new graphics depend on physics you would like to understand**

References of global particle simulations

1. **"Solar wind-magnetosphere interaction as simulated by a 3D EM particle code," Buneman, O., T. Neubert and K.-I. Nishikawa,** *IEEE Trans. Plasma Sci., 20*, **810, 1992.**
2. **"Solar wind-magnetosphere interaction as simulated by a 3D EM particle code," Buneman, O., K.-I. Nishikawa, and T. Neubert, in** *Space Plasmas: Coupling Between Small and Medium Scale Processes, Geophys. Monogr. Ser.,* **vol. 86, edited by M. Ashour-Abdalla, T. Chang, and P. Dusenbery, p. 347, AGU, Washington D.C., 1995.**
3. **"Particle entry into the magnetosphere with a southward IMF as simulated by a 3-D EM particle code," Nishikawa, K.-I.,** *J. Geophys. Res., 102*, **17,631, 1997.**
4. **"Reconnections at near-Earth magnetotail and substorms studied by a 3-D EM particle code," Nishikawa, K.-I.,** *Geospace Mass and Energy Flow: Results From the International Solar-Terrestrial Physics Program, Geophys. Monogr. Ser.,* **vol. 104, edited by J. L. Horwitz, W. K. Peterson, and D. L. Gallagher, p. 175, AGU, Washington D.C., 1998.**

5. “**Particle entry through reconnection grooves in the magnetopause with a dawnward IMF as simulated by a 3-D EM particle code**,” **Nishikawa, K.-I.,** *Geophys. Res. Lett., 25*, **1609, 1998.**

6. “**Evolution of thin current sheet with a southward IMF studied by a 3-D EM particle code**,” **Nishikawa, K.-I. And S. Ohtani,** *J. Geophys. Res., 105*, **13,017, 2000.**

7. “**Global Particle Simulation for a Space Weather Model: Present and Future,**” **Nishikawa, K.-I. And S. Ohtani,** *IEEE Trans. Plasma Sci., 28*, **1991, 2000.**

8, “**Global particle simulation study of substorm onset and particle acceleration**,” **Nishikawa, K.-I.,** *Space Sci. Rev., 95*, **361, 2001.**

9. “**Visualization and criticality of three-dimensional magnetic field topology in the magnetotail**,” **Cai, D.-S., Y. Li, T. Ichikawa, C. Xiao, and K.-I. Nishikawa,** *Earth Planets Space,* **in press, 2001.**

Future Plans

•Run simulations with better resolutions using **HPF Tristan** code on **ORIGIN2000**

•Simulations related to magnetic storms including **magnetic plasma clouds**

•Using satellite date for initial solar wind conditions, perform **case studies** to compare with observations

•**Improve 3-D displays** in order to understand physics involved with Techplot, **AVS**

•Implement **a better ionospheric model including ionospheric outflows**

•Investigate **high energy particle injections** into the ionosphere

•**Predict energetic particle injection** in conjunction with magnetic storms with typical solar wind parameters

•Investigate the dayside magnetopause including Cluster observations

•Plan and asses multi-satellite missions (MMS, MC DRACO)